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Assessment of impacts of climate change on water resources – a case study of the Great Lakes of North America

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Abstract

Historical trends in precipitation, temperature, and streamflows in the Great Lakes are examined using regression analysis and Mann-Kendall statistics, with the result that many of these variables demonstrate statistically significant increases ongoing for a six decade period. Future precipitation rates as predicted using fitted regression lines are compared with scenarios from Global Climate Change Models (GCMs) and demonstrate similar forecast predictions for Lake Superior. Trend projections from historical data are, however, higher than GCM predictions for Michigan/Huron. Significant variability in predictions, as developed from alternative GCMs, is noted. Given the general agreement as derived from very different procedures, predictions extrapolated from historical trends and from GCMs, there is evidence that hydrologic changes in the Great Lakes Basin are likely the result of climate change.

1 Introduction

The Great Lakes of North America, namely Lake Superior, Huron, Michigan, Erie and Ontario, represent one of the most important water resources in the world, and provide water for multipurposes for more than fifty million people in eastern North America. Combined, the Great Lakes and their connecting channels comprise the largest fresh surface water system on earth (Fig. 1), holding approximately 20 percent of the world's fresh surface water supply (De Loë, 2000; GLIN, 2005). As an indication of the enormous size of the lakes, the estimated cumulative volume of the five lakes is 6×10^{15} (six quadrillion) gallons which is sufficient water to flood North America to a depth of 1 metre. The diversity of uses and the magnitude of the Great Lakes system interactions are testimony to the enormous importance of this freshwater system. However, the Great Lakes basin represents a drainage area of 770 000 km^2 in the United States and Canada (Croley II, 1990) while the water surface area is 244 000 km^2 (US EPA, 2005); it follows that the Great Lakes drain land areas only twice that of their surface area so that changes in land use have not been responsible (to a significant degree) for changes in annual flows discharging from portions of, and/or all of, the Great Lakes system. As a consequence, the lengthy record of historical data allows assessment whether there are stresses acting on the Lakes, as a result of climate change. Specifically, global climate changes may be occurring, resulting in changes in precipitation, temperature, and flows, in terms of the water budget for the Great Lakes. As a result of the size of the Lakes, there is continuing potential for water diversions to be constructed to divert flow from the Great Lakes, to export water to dry areas of North America such as the mid-western states of the USA (e.g. Dulmer et al., 2003). While the general tenor of discussion is for continued rejection of these scenarios, issues of sustainability of, and diversions from, the Great Lakes will intensify in the future decades particularly if global warming intensifies. As a result of the above, while there are enormous volumes of water in the Great Lakes, the relatively modest contributing drainage areas translate to enormous detentions times for the Great Lakes, as summarized in Table 1. Hence, while the dimensions of the Great Lakes imply at first "glance" that they might support diversion of large quantities of water out of the watershed, any changes arising from climate change or water diversions may create longterm repercussions on water levels and water budgets. The result is an enormous need to understand the extent to which climate change is occurring. To address this issue, investigation procedures described herein include assessment of climate change impacts on the Great Lakes by:

(i) a review of historical trends of precipitation, temperatures and flows, and extrapolation of these historical trends to assess potential future scenarios; and,

(ii) estimation of the hydrologic impacts of climate change using global climate models (GCMs). This paper utilizes both (i) and (ii) items, to provide insights into projected future possibilities for the Great Lakes.

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2 Global climate change and climate change models

Trace constituents within the atmosphere, particularly water vapour, carbon dioxide, methane and ozone, function much like a "thermal blanket" around the earth. These constituents, commonly referred to as greenhouse gases, collectively total less than one percent of the atmosphere, but are extremely important in retarding the release of heat energy from the earth back into space. This natural "greenhouse effect" keeps the earth's average surface temperatures approximately 30°C warmer than simple radiation physics would suggest for a transparent atmosphere. IPCC (1996) reported that the current scientific estimate of the chemical composition of the atmosphere clearly indicates that concentrations of principal greenhouse gases are increasing rapidly, and appear already to exceed significantly, peak concentrations of the past 160 000 years. Hengeveld (2000) stated that although the paleoclimatological and historical records trends are helpful to understand the cause and effect relationships within the climate system, climatologists still turn to computer simulations or Global Climate Models (GCMs) to assess the global scale response of the system to changes in radiative forcing functions. These models are based on fundamental principles of physics and are being tested against climate observations, to assess their ability to simulate adequately, the global climate change system. A number of these models have been developed and used for predicting climate changes. The most frequently employed GCMs include the Goddard Institute for Space Studies (GISS) after Hansen et al. (1983), Geophysical Fluid Dynamics Laboratory (GFDL) after Manabe and Weatherald (1980) and Canadian Climate Centre (CCC) after Boer (1992). Gleick (1986, 1987) has indicated that the regional hydrologic impacts arising from the GCMs are not reliable at a regional scale for hydrologic variables and suggests that it is necessary to couple the climate models' scenarios with a hydrologic model to approximate the impact of climate change on regional water resources. As an example, one of the future climate model scenarios that have been developed is a doubling of atmospheric carbon dioxide which has been predicted to occur in the mid 21st century. The concern is that the increasing carbon dioxide concentrations in the atmosphere in the last thirty years (which have been documented), will result in increased warming of the earth's surface.

3 Assessment of historical trends

In the Great Lakes Basin, both empirical and aerodynamic techniques have been used to estimate evapotranspiration, and studies conducted by Cohen (1986, 1990), Sanderson (1987), and Croley (1990, 2004) have found that evapotranspiration would be significantly increased under climate change scenarios. Sanderson and Smith (1990, 1993) used the Thornthwaite model and Smith and McBean (1993) used the HELP model and predicted twenty to thirty percent increases in potential evapotranspiration and approximately a 15% increase in actual evaporation to occur. In addition to the above, the IPCC (1996) indicates there will be an increase of 1.5 °C to 4.5 °C in global mean temperature, and a 3 to 15 percent increase in precipitation in response to climate change. As evident from numerous dimensions described above, there are numerous dimensions suggestive of climate change projections.

3.1 Historical data assembles

The Great Lakes Environmental Research Laboratory (GLERL) of the National Organization for Atmospheric Administration (NOAA) archives lengthy records of hydrologic data for the Great Lakes (NOAA, 2004). For this research, overlake air temperature, and overlake precipitation data for the individual Great Lakes and the flow data for their connecting channels (St. Mary's River, St. Clair River, Niagara River, and St. Lawrence River as indicated in Fig. 1) were collected from NOAA. For the Great Lakes, overlake air temperature data are available for the period 1948–2000 (NOAA, 2004). Overlake precipitation data are estimated from the records of nearshore stations and these data have been spatially weighted by using the modified Theissen weighting approach (Croley et al., 2004). As cited in Croley et al. (2004), Quinn and Norton (1982) computed 1930–1947 monthly precipitation using 5 km grid while Croley et al. (2004) used 1 km grid. For the current study, the precipitation data were extracted for the period of 1930–1990. According to Croley et al. (2004), “Lake outflows are determined by direct measurement (for Lakes Superior and Ontario), stage-discharge relationships (for Lakes Michigan, Huron, and St. Clair), or a combination (Lake Erie) and are generally considered accurate within 5%”. For this research, the flow data were extracted for the period of 1930–1990 to coincide with the precipitation records.

3.2 Trend characterization methodology

3.2.1 Regression model

There exist a number of parametric and nonparametric methods for detection of trend (e.g. McBean and Rovers, 1998). One of the most useful parametric models to detect the trend is the “Simple Linear Regression” model. The method of linear regression requires the assumptions of normality of residuals, constant variance, and true linearity of relationship (Helsel and Hirsch, 1992). The model for Y (e.g. precipitation) can be described by an equation of the form:

$$Y = a \times t + b \quad (1)$$

where,
t= time (year)
a= slope coefficients; and
b= least-square estimates of the intercept

The slope coefficient indicates the annual average rate of change in the hydrologic characteristic. If the slope is statistically significantly different from zero, the interpretation is that it is entirely reasonable to interpret there is a real change occurring over time, as inferred from the data. The sign of the slope defines the direction of the trend of the variable: increasing if the sign is positive, and decreasing if the sign is negative.

3.2.2 Mann-Kendall model

Simple linear regression analysis may provide a primary indication about the presence of trends in the time-series data. Other methods, such as the non-parametric Mann-Kendall test, which is commonly used for hydrologic data analysis, can be used to detect trends that are monotonic but not necessarily linear. The Mann-Kendall test does not require the assumption of normality, and only indicates the direction but not the magnitude of significant trends (USGS, 2005 ; Helsel and al., 1992). The Mann-Kendall procedure was applied to the time series of annual precipitation, annual mean temperature, and the average annual flows. The computational procedure for the Mann-Kendall test is described (e.g. see Adamowski and Bougadis, 2003). Let the time series consists of n data points and T_i and T_j are two sub-sets of data where i= 1, 2, 3, ...,n-1 and j= i+1, i+2, i+3, ...,n. Each data point T_i is used as a reference point and is compared with all the T_j data points such that:

$$\mathrm{sign(T)} = \begin{cases} 1 & \text{for} \quad T_j \rangle T_i \\ 0 & \text{for} \quad T_j = T_i \\ -1 & \text{for} \quad T_j \langle T_i \end{cases} \tag{2}$$

The Kendall's S-statistic is computed as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sign}(T_j - T_i) \tag{3}$$

The variance for the S-statistic is defined by:

$$\sigma^2 = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i(i)(i-1)(2i+5)}{18} \tag{4}$$

in which t_i denotes the number of ties to extent i. The summation term in Eq. (4) is only used if data series contains the "tied" values. The test statistic, Z_s, can be calculated

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as:

$$Z_s = \begin{cases} (S-1)/\sigma & \text{for} \quad S \rangle 0 \\ 0 & \text{for} \quad S = 0 \\ (S+1)/\sigma & \text{for} \quad S \langle 0 \end{cases} \tag{5}$$

In which Z_s follows a standard normal distribution. Equation (5) is useful for record lengths greater than 10 and if the number of tied data is low (Kendall, 1962). The test statistic, Z_s is used as a measure of significance of trend. In fact, this test statistic is used to test the null hypothesis, H_0: There is no monotonic trend in the data. If $|Z_s|$ is greater than $Z_{\alpha/2}$ here α represents the chosen significance level (usually 5%, with $Z_{0.025}$=1.96), then the null hypothesis is invalid, meaning that the trend is significant. For this study, the simple regression analysis technique is used to test the slopes of the trend lines for statistical significance at 5% level. The Mann-Kendall trend test procedure is applied to further verify the outcomes of regression analysis for the hydrological variables considered.

4 Precipitation, temperature and flow trends

4.1 Historical precipitation trends

Precipitation trend characterization is challenging since precipitation varies substantially across space and time, and hence difficult to predict a significant long-term change (Mortsch et al., 2000). Nevertheless technical literature reveals there is evidence of increasing trend of precipitation; Mortsch et al. 2000) reported annual precipitation trends for regions of Canada near the Great Lakes region are significantly increasing. As well, Filion (2000) cited that Coulson's (1997) results indicate a precipitation increase of 7–18% in northern British Columbia. The long-term precipitation data (1930–1990) for the individual Great Lakes are plotted as annual precipitation versus time in Fig. 2, "a" through "e". The slopes of the trend lines are highly significant from both the regression modeling and using the Mann-Kendall statistic and low significance

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for Lake Superior, as summarized in Table 2. These results demonstrate there is sufficient evidence to indicate (on the basis of 1930–1990 period) an increasing trend in precipitation on the Great Lakes.

4.2 Trends in temperature

Average annual trends of overlake Temperature versus time (1948–2000), are illustrated in (Fig. 3 “a” through “e”). The significance of the long-term temperature data for the individual Great Lakes were tested with the results as summarized in the Table 3. None of the trends for temperature were identified as statistically significant at 5% level; the slopes of the regression lines were all positive.

4.3 Trends in measured flows

Flow data were analyzed for four locations at various points along the Great Lakes system namely (I) St. Mary’s River, (II) St. Clair River, (III) Niagara River, and (IV) St. Lawrence River, as identified in Fig. 1. These locations represent the sequential locations within the Great Lakes Watershed. The flow magnitudes over time are plotted in Fig. 4 (4-a: St. Mary’s River, 4-b: St. Clair River, 4-c: Niagara River, and 4-d: St. Lawrence River). For 1930–1990, linear regression slopes of the trend lines are highly significant (at 5% level) for all channels except for St. Mary’s River which was low significance. The Mann-Kendall trend test confirms the trend statistics, as summarized in Table 4.

5 Comparison of historical trend projections and GCM predictions

If the historical trends continue, the magnitudes of precipitation and flow can be assessed for future years, and hence provide a comparison with the projections using the GCMs. It is noted that scenarios of climate change have typically been structured as percent change from the 1960–1990 period, as a means of establishing a baseline relative to, for example, the year 2050, the projected year in which there is considered the potential for a doubling of CO_2 in the atmosphere (e.g. after Lofgren et al., 2002). In this context, trend extrapolation of the historical data using the regression equations for each of precipitation, temperatures, and flows, are summarized in Tables 5 through 7, respectively.

5.1 Prediction of precipitation magnitudes in response to climate change

GCMs are being used to develop future scenarios under changed climate conditions (Mortsch et al., 2000). For illustration purposes, the GCM predictions for future changes in precipitation for Lake Superior, Lake Michigan and Lake Huron (the latter two combined to Michigan/Huron) from Lofgren (2002) are plotted in Figs. 5(a) and (b). Lofgren et al. (2002) results show that different GCMs produce significantly different predictions; they used outputs from two different types of GCMs namely the equilibrium models (GISS, GFDL, OSU, and CCC1) and the transient models (CGCM1, HadCM2, GFTR2, HCTR2, MOTR2, and CCTR2). The equilibrium models are models that are allowed to run until they reach equilibrium with a predefined atmospheric condition e.g. $2\times CO_2$. On the contrary, transient models are full dynamic ocean models that are run coupled with an atmosphere with greenhouse content changing with time (Lofgren et al., 2002). In addition to the GCM predictions, also plotted on Figs. 5(a) and (b) are extrapolations using the observed, historical records. As illustrated in Fig. 5(a), for Lake Superior, compared to the prediction by regression, some GCMs overestimate the change in precipitation while some underestimate. For Fig. 5(b), for Michigan/Huron Lakes, the predictions by the regression lines exceed GCM model predictions.

5.2 Prediction of temperature changes to year 2050

According to IPCC, global temperatures are expected to increase by 1.5°C to 4.5°C (IPCC, 1996) as opposed to the trend extrapolation of historical data of 0.63 °C (from Table 6). Upon analyzing the data for the period 1895–1999, Mortsch (2000) suggested that the annual average temperature for Canada has warmed by a statistically significant 1.3°C, although the warming is not consistent throughout the time span. The continuation of change in temperature from the observed records can be compared with GCMs' prediction of future temperature. The GCMs' predictions are consistently higher than those extrapolated from the historical data as listed in Table 7. Even different GCM predictions are demonstrated as varying amongst themselves by substantial amounts, indicating there are substantial levels of uncertainty associated with temperature predictions.

5.3 Prediction of flows to year 2050

The impacts of climate change on water resources are potentially large. Increases in precipitation and temperature could result in dire consequences on water quantity and quality. Precipitation directly translates into runoff, and the regions that experience significant increases in precipitation are likely to have increases in runoff and streamflows although land use changes may also influence runoff magnitudes. One of the major impacts of climate change would be the changes in frequency and magnitude of extreme hydrologic events (e.g. more intensive rainfall events). Incidence of heavier rainfall events could result in more rapid runoff and greater flooding. As well, heavier rainfall may cause deterioration of water quality. Increased rainfall intensity and high magnitude of floods may result in increased erosion of the land surface and the stream channels, higher sediment loads, and increased loadings of nutrient and contaminants. Based on the observed historical records, annual precipitation rates are significantly increasing over the Great Lakes. This increase in precipitation results in increased streamflows in the Great Lakes system (as apparent from Table 4). The rate of increase in streamflows over the 60 years period (1930–1990) is alarming. From Table 8, the rate of predicted increases in streamflows at the outlet of Lake of Superior, Lake Huron, Lake Erie, and Lake Ontario till 2050 is 11%, 33%, 31%, and 34%, respectively.

6 Conclusions

Historical records of precipitation, temperature, and streamflows in the Great Lakes system using simple linear regression analysis and non-parametric Mann-Kendall trend test, demonstrate statistically significant increases in precipitation and streaflows over the period 1930–1990. Flow in the St. Mary's River (outlet of the Lake Superior) shows a gentle increasing trend, whereas flows in the connecting channels at St. Clair River, Niagara River, and St. Lawrence River show statistical significance (at 5% level) trends. Temperature trends were not found to be statistically significant (at 5% level) for any of the five Great Lakes, although the line fitted by regression shows a gentle increasing slope (an increase of 0.63°C) and less in magnitude than the GCM predictions. The presence of significant positive trends in historical precipitation and flows, and comparable levels as predicted by the GCMs, indicate that the hydrologic changes being incurred in the Great Lakes system may be attributable to climate change.

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Table 1. Retention Times for the Great Lakes.

Individual Lake	Rank in World [a] by area	Rank in World [a] by volume	Retention Time (years) [b]
Superior	2	4	191
Michigan	4	6	99
Huron	5	7	22
Erie	11	–	2.6
Ontario	–	12	6

Sources: Beeton (2002) [a] and USEPA (2005) [b].

Table 2. Statistical trend tests for overlake precipitation versus time.

	Regression Statistics		Mann-Kendall Statistics		
Lake	Regression Equation*	Statistical Significance F**	Kendall's S	Z_s	Significance at 5% level
Superior	Y=0.507 t – 202.8	0.43 (low significant)	65	0.404	NO
Michigan	Y= 1.9031 – 2983	0.005 (highly significant)	440	2.74	YES
Huron	Y= 1.801 t – 2712	0.0032 (highly significant)	447	2.78	YES
Erie	Y= 3.509 t – 5981	0.0001 (highly significant)	595	3.7	YES
Ontario	Y= 2.45 t – 3944	0.0002 (highly significant)	599	3.75	YES

$Z_{0.025} = 1.96$

Legend:
* t= Time
** The smaller the F, the more significant the trend.
Lesser than 0.01 means highly significance.

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Table 3. Statistical trend tests for temperatures versus time.

	Regression Statistics		Mann-Kendall Statistics		
Lake	Regression Equation*	Statistical Significance F **	Kendall's S	Z_s	Significance at 5% level
Superior	Y=0.0163 t – 28.194	0.04 (low significant)	– 48	0.5	NO
Michigan	Y= 0.001 t + 5.8435	0.88 (low significant)	– 84	0.88	NO
Huron	Y=0.0004 t + 6.0524	0.95 (low significant)	– 136	1.4	NO
Erie	Y = 0.0075 t – 5.4803	0.26 (low significant)	– 78	0.81	NO
Ontario	Y = 0.0051 t – 1.8885	0.41 (low significant)	– 44	0.46	NO

$Z_{0.025} = 1.96$

Legend:
* t = Time
** The smaller the F, the more significant the trend.
Lesser than 0.01 meanshighly significance.

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Table 4. Results of statistical trend tests for time series of flows in connecting channels.

	Regression Statistics		Mann-Kendall Statistics		
River	Regression Equation *	Statistical Significance F **	Kendall's S	Z_s	Significance at 5% level
St. Mary's	Y=3.428 t – 4503	0.2 (low significant)	213	1.325	NO
St. Clair	Y=31.527 t – 54807	$8*10^{-8}$ (highly significant)	801	4.99	YES
Niagara	Y= 23.955 t – 41148	$5*10^{-8}$ (highly significant)	825	5.13	YES
St. Lawrence	Y= 32.3 t – 56315	$3*10^{-8}$ (highly significant)	826	5.1	YES

$Z_{0.025} = 1.96$

Legend:
* t = Time
** The smaller the F, the more significant the trend.
Lesser than 0.01 means highly significance.

Table 5. Predicted changes in precipitation to 2050 from historical trend projections.

Lake	Average Annual Precipitation(mm) (1960–1990)	Trend Extrapolation for Precipitation 2050(mm)	Percentage Change in Precipitation(%)
Superior	795	837	5.2
Michigan	830	975	17.5
Huron	854	998	16.9
Erie	928	1212	30.6
Ontario	875	1068	22

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Table 6. Predicted changes in temperatures to 2050 from historical trend projections.

Lake	Average (1960–1990) Temperature (˚C)	Trend Extrapolation For Temperature 2050 (˚C)	Predicted Change (˚C)
Superior	3.7	5.2	1.5
Michigan	7.7	7.9	0.2
Huron	6.6	6.9	0.3
Erie	9.1	9.9	0.8
Ontario	8.0	8.37	0.4
		Average	0.63

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Table 7. Comparison of future temperatures for projections from historical trends and GCMs.

Lake	Average Temperature (˚C) of Base case (1960–1990)	Projected Temperature (˚C) for 2050			
		From Historical Trends projections	From GCMs [a]		
			GISS	GFDL	OSU
Superior	3.7	5.2 (1.5)	6.6 (2.9)	9.5 (5.8)	5.7 (2.0)
Michigan	7.7	7.90 (0.2)	11.9 (4.2)	13.4 (5.7)	10.7 (3.0)
Huron	6.6	6.90 (0.3)	9.9 (3.3)	11.7 (5.1)	8.6 (2.0)
Erie	9.1	9.9 (0.8)	13.8 (4.7)	14.8 (5.7)	12.5 (3.4)
Ontario	8.0	8.37 (0.37)	11.8 (3.8)	13.1 (5.1)	10.4 (2.4)
Average	7.02	7.65 (0.63)	10.8 (3.8)	12.5 (5.5)	9.6 (2.6)

Note: values within parentheses represent the change in projected temperature compared to the Base Case (1960–1990) mean. a= Values extracted from Croley (1990).

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Table 8. Predicted changes in flows to 2050 from historical trend projections.

River	Average Annual Flow (m^3/s) (1960–1990)	Trend extrapolation for Flows to 2050(m^3/s)	Predicted Percentage Change (%)
St. Mary (Outlet of Lake Superior)	2267	2524.4	11.4
St. Clair (Outlet of Lake Huron)	7370	9823	33.3
Niagara (Outlet of Lake Erie)	6083	7960	30.9
St. Lawrence (Outlet of Lake Ontario)	7366	9900	34.4

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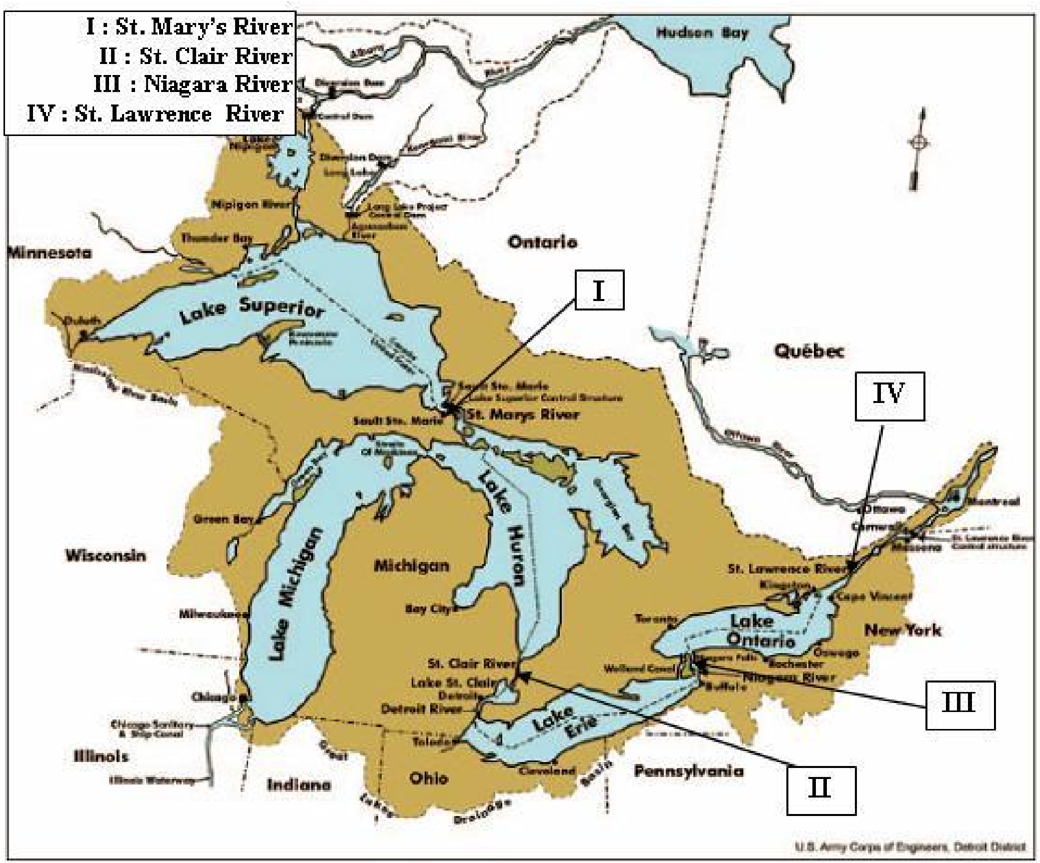

Fig. 1. The Great Lakes Basin.

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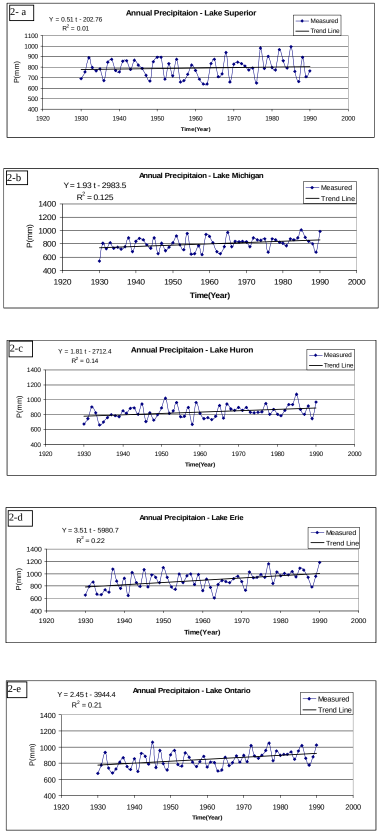

Fig. 2. ("a" through "e") – Annual average precipitations versus time.

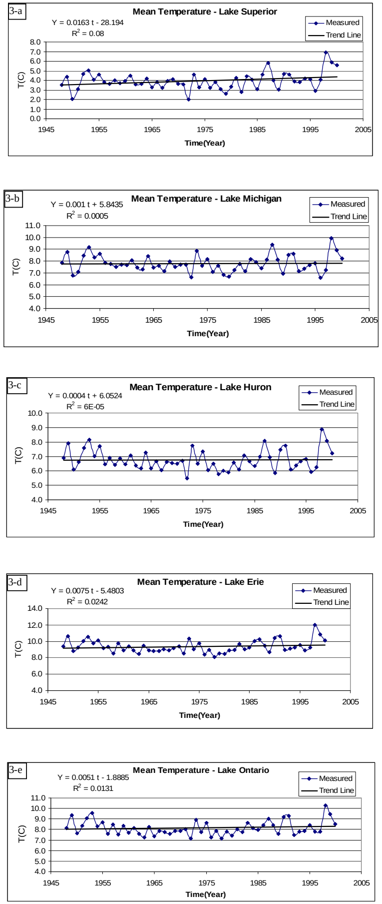

Fig. 3. ("a" through "e") – Annual average temperatures versus time.

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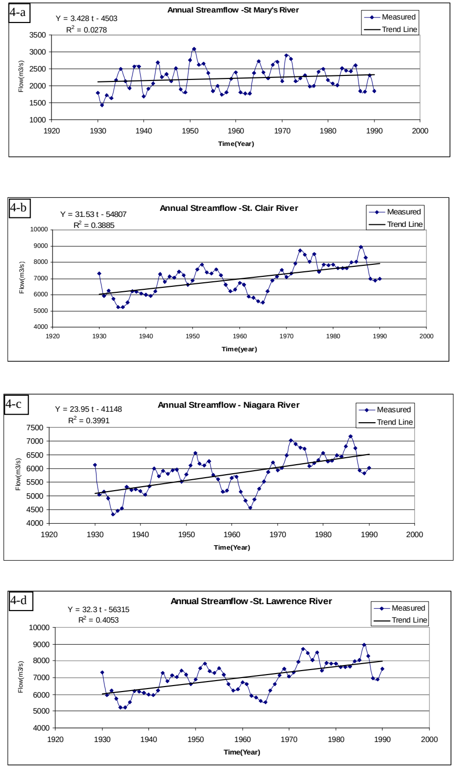

Fig. 4. ("a" through "d") – River flows at various locations within the Great Watersheds versus Time.

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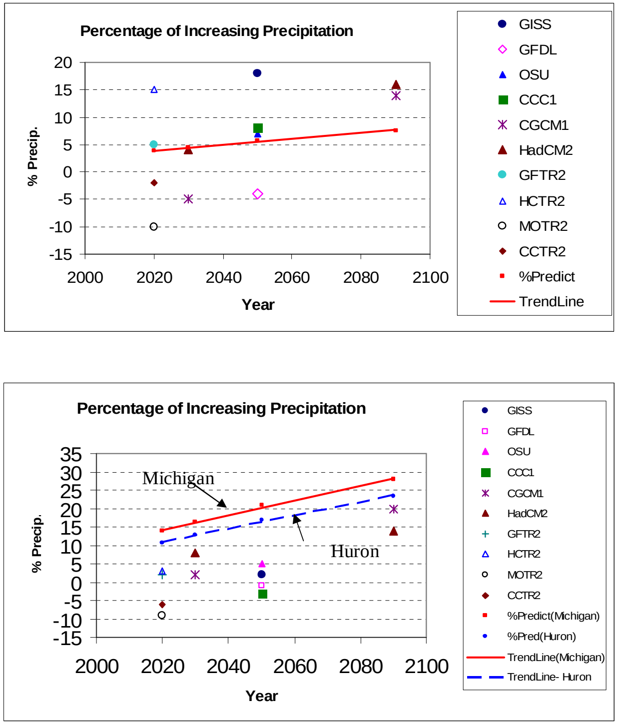

(a)

(b)

Fig. 5. **(a)** Comparison of results of GCMs models by Lofgren et al. (2002) with predicted model in Lake of Superior. **(b)** Comparison of results of GCMs models by Lofgren et al. (2002) with predicted model in Lake Michigan and Lake Huron.